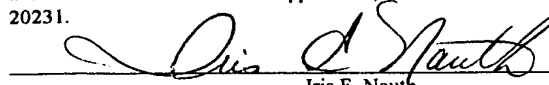


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Thereby certify that this Communication and documents referred to as enclosed therein are being deposited with the United States Postal Service on **October 1, 2001** in an envelope as "Express Mail Post Office to addressee," **Mailing Label Number EL852682200US**, addressed to the Box Patent Application, Commissioner of Patents, Washington, D.C. 20231.


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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of : BROWN, et al.
For : **SiC PHOTODIODE DETECTORS
FOR RADIATION DETECTION
APPLICATIONS**
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COMMUNICATION

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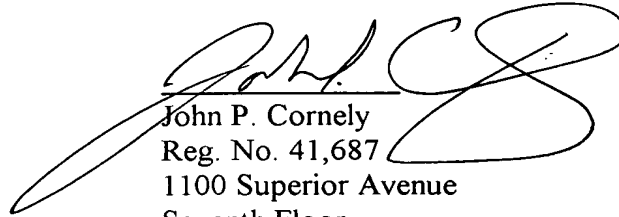
Dear Sirs:

Applicant filed the above-referenced patent application with the United States Patent and Trademark Office (USPTO) today, October 1, 2001 via the Electronic Filing System (EFS).

A courtesy copy of the application including the drawings, which represents the subject matter applicant intended to file via the EFS, is enclosed.

Respectfully submitted,

**FAY, SHARPE, FAGAN,
MINNICH & MCKEE, LLP**

A large, stylized handwritten signature in black ink, appearing to read 'John P. Cornely', is written over a horizontal line.

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SIC PHOTODIODE DETECTORS FOR RADIATION DETECTION APPLICATIONS

BACKGROUND OF THE INVENTION

The present invention relates generally to photodiode detectors for radiation detection applications. It finds particular application in conjunction with silicone carbide detectors and will be described with particular reference thereto. It will be appreciated, however, that the invention is also amenable to other like applications.

Present detector systems for computed tomography (CT) use silicon (Si) diodes in combination with a scintillator plate. The scintillator converts x-rays to visible light photons whereupon a Si photodiode converts these photons to photocurrent. There are numerous problems associated with the use of Si photodiodes. Such problems will become limiting factors for future CT machines.

For example, Si diodes are prone to radiation damage. Radiation damage increases dark current, which decreases internal impedance. Decreased internal impedance results in gain changes, increases in noise level, and makes the conversion of photons to hole-electron pairs less efficient.

Future CT will utilize smaller pixels (individual diode areas), which will produce smaller signal levels. Small signal levels mean that the difference between dark current and signal levels will be much smaller. The dark current level produces an offset. Because the signal level will only be a small factor above the dark current, the dynamic range of the system will be compromised.

Present CT machines are working on the edge of thermal drift problems due to changes in the dark current of Si diodes. The offsets need to be constantly monitored before every scan and corrections are then made to the data for anticipated

drift during the scan. This problem will be more severe whenever, as planned, a more powerful x-ray tube is utilized.

More rapid scans will be used in advanced CT machines, which will require faster response scintillators. Present scintillators, which have light wavelength output matched to Si, are slow to respond and contain a light output "tail" that decays slowly. Back calculations are required to correct for the slow decay. Consequently, it follows that newer, faster CT machines will require such back calculations to be performed at even faster rates. In fact, the rates at which the back calculations would need to be performed are impractical and, possibly, unachievable.

Oil exploration drilling, for example, uses photo multiplier tubes (PMTs) to detect gamma rays and neutron radiation. This application is similar to the CT application described above in that the detector utilizes a scintillator crystal to convert the gamma and neutron radiation into visible light whereupon the PMT converts this light signal into an electric signal.

The PMTs are extremely expensive and, furthermore, not very reliable (e.g., the failure rate of the PMTs at the bottom of a well near a drill bit is very high). The supply of good PMTs is limited and sorting through hundreds may be required to find a few good ones. Another problem is that the noise of the PMT increases with temperature. Deep hole drilling experiences temperatures as high or higher than 150°C and the increase in PMT noise makes it more difficult to detect radiation. The low reliability of PMTs significantly contributes to the cost of oil exploration drilling. Therefore, more reliable detectors are desirable.

The present invention provides a new and improved apparatus and method which overcomes the above-referenced problems and others.

BRIEF SUMMARY OF THE INVENTION

In accordance with one aspect of the invention, a radiation detector is provided. It includes: a scintillator which produces UV photons in response to receiving radiation from a radiation producing source; and, a wide bandgap semiconductor device

sensitive to the UV photons produced by the scintillator. The semiconductor device produces an electric signal as a function of the amount of UV photons incident thereon.

In accordance with another aspect of the invention, the wide bandgap semiconductor device is a SiC, GaN or AlGaN device.

In accordance with a more limited aspect of the invention, the semiconductor device is a photodiode, an avalanche photodiode or an array of the same.

In accordance with another aspect of the invention, the wide bandgap semiconductor device has a dark current of less than or equal to about 1.0 pA/cm^2 at about 0.5 VR.

In accordance with yet another aspect of the invention, the wide bandgap semiconductor device has a bandgap greater than or equal to about 2 eV. Preferably, the bandgap is about 3 eV.

In accordance with another aspect of the invention, an output of the UV photons from the scintillator substantially matches a responsivity of the wide bandgap semiconductor device.

In accordance with still another aspect of the invention, the scintillator is any one of a number of UV scintillators such as those including Li_2HfO_3 , BaF_2 , CsI, CeF_3 , $\text{LuAlO}_3\text{:Ce}^{3+}$, or $\text{Lu}_3\text{Al}_5\text{O}_{12}\text{:Pr}^{3+}$.

In accordance with another aspect of the invention, the radiation detected is gamma rays or x-rays.

One advantage of the present invention is that it uses a photodiode technology having a relatively large yield (e.g., about 50% to 80%).

Another advantage of the present invention is that it incorporates a photodiode having a relatively wide bandgap.

Another advantage of the present invention is that it produces a relatively low dark current.

Another advantage of the present invention is that, because of the wide bandgap and low dark current, it reduces and/or eliminates detector thermal drift problems and detector noise.

Another advantage of the present invention is that SiC photodiodes are more radiation hard than Si photodiodes.

Still further advantages of the present invention will become apparent to those of ordinary skill in the art upon reading and understanding the following detailed description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating a preferred embodiment and are not to be construed as limiting the invention.

FIGURES 1A and 1B illustrate systems for measuring radiation in accordance with aspects of the present invention.

FIGURE 2 illustrates a curve representing dark current versus voltage for a SiC photodiode in accordance with aspects of the present invention.

FIGURE 3 illustrates one exemplary application of the present invention in connection with an exploratory oil drill apparatus.

FIGURE 4 illustrates an aspect of the present invention wherein a semiconductor device includes an array of photodiodes.

FIGURE 5 illustrates an embodiment of the present invention employing a trumpet reflector.

FIGURE 6 illustrates another exemplary application of the present invention in connection with a medical imaging apparatus.

DETAILED DESCRIPTION OF THE INVENTION

FIGURE 1A is a diagrammatic illustration showing a system **10** for measuring radiation **12**. The system **10**, for example, is a radiation detector. Also shown is a radiation source **14** which produces the high energy radiation **12**. The system **10** includes: a scintillator or other like means **16** for converting the radiation **12** incident thereon into ultra-violet (UV) photons **20**; a photodetector means **22** for producing an

electric current as a function of an amount of UV photons **20** incident thereon; and, a meter **24** which measures the amount of electric current produced by the photodetector means **22**. The high energy radiation **12** produced by the radiation source **14** preferably includes gamma rays and/or x-rays. The means **16** receives the radiation **12** from the source **14** and converts the radiation **12** into the UV photons **20**. The number of UV photons **20** produced by the means **16** is proportional to the amount of radiation **12** received from the source **14**.

In the alternate embodiment shown in FIGURE 1B, the electrical signal from the photodetector means **22** is amplified by an amplifier **60**. The amplified signal is then routed to an analog-to-digital (A/D) converter **62** which samples the analog signal and generates a digital output data stream therefrom. The output data stream is then sent to a computer **64** for analysis.

The means **16** for converting the radiation **12** into UV photons **20** is preferably a scintillator of the usual type. The scintillator **16** converts the high energy radiation **12** incident thereon into UV photons **20**. For example, suitable UV photon producing scintillators include Li_2HfO_3 , BaF_2 , CsI , CeF_3 , $\text{LuAlO}_3\text{:Ce}^{3+}$, or $\text{Lu}_3\text{Al}_5\text{O}_{12}\text{:Pr}^{3+}$. Furthermore, the photodetector means **22** for producing the electric current is preferably a wide bandgap semiconductor device, which is sensitive to energy in the UV region. As used herein, the term "wide bandgap" refers to a bandgap greater than or equal to 2 eV. The bandgap for the semiconductor device **22** is, preferably, about 3 eV.

In a preferred embodiment, the semiconductor device **22** includes silicon carbide (SiC), GaN or AlGaIn, and, in this sense, is a SiC, GaN or AlGaIn device, respectively. The device **22** is preferably a photodiode or an avalanche photodiode. That is, the semiconductor device **22** is optionally a SiC, GaN or AlGaIn photodiode or a SiC, GaN or AlGaIn avalanche photodiode, or an array of the same. In any event, the semiconductor device **22** is sensitive to the UV photons produced by the UV scintillator **16**. In this manner, the output of the scintillator **16** substantially matches a responsivity of the photodiode **22**. Consequently, the semiconductor device **22** produces an electric current or signal as a function of a number of the UV photons **20** received from the scintillator **16** (e.g., the number of UV photons impinging the device **22**). Because the

scintillator **16** produces a photon flux proportional to the energy of the radiation photon (gamma or x-ray), the output of the semiconductor device **22** is likewise proportional to the radiation energy.

With reference to FIGURES 1 and 2, a curve **30** representing a dark current of the semiconductor **22** versus a voltage shows the semiconductor **22** exhibits a dark current of less than or equal to about 1.0 pA/cm^2 at about $0.5 V_R$ or reverse voltage. Therefore, the photodiode **22** has a relatively low dark current. Furthermore, the yield of the photodiodes **22** is very large (e.g., about 50% to 80%). The use of SiC photodiodes reduces and/or eliminates detector thermal drift and noise problems because the dark current is extremely low because of the wide bandgap (e.g., preferably about 3 eV). Consequently, any increase in dark current is negligible.

FIGURES 3 through 6 illustrate exemplary applications of the present invention. For convenience, components of the embodiments illustrated in FIGURES 3 through 6, which correspond to the respective components of the embodiment illustrated in FIGURES 1A and 1B, are given the same numerical references. New components are designated by new numerals.

With reference to FIGURE 3, the system **10** for measuring radiation **12** includes a cavity **40** having a mirrored inner surface **42**. In the preferred embodiment, the cavity **40** is defined by a reflector **44** having an ellipsoidal shape. The scintillator **16** is positioned within the reflector **44**; the photodetector means **22** is positioned at a focal point of the reflector **44**. Such a configuration is used, for example, within an oil drilling exploration application. In this application, the reflector **44** is pointed toward a material (e.g., rock) that is a source **14** of high energy radiation **12** (e.g., gamma rays and/or x-rays). The emission of high energy radiation **12** from rocks and the like is indicative of a sought substance, e.g., oil. More specifically, the higher the level of radiation measured, the more likely it is that oil is present. In this embodiment, the system **10** is contemplated to include a single scintillator **16** and a single device **22** (e.g., a photodiode). However, other configurations are also contemplated. See, e.g., FIGURE 4 which shows the semiconductor device **22** as an array of photodiodes **22a** abutted directly to the rearward end of the scintillator **16** which faces the radiation source **14**.

FIGURE 5 shows an embodiment of the system **10** which incorporates a trumpet reflector **70** that houses the scintillator **16** at its flared end. The UV photons **20** produced by the scintillator **16** are reflected back and forth off the reflective walls of the trumpet reflector **70**. Eventually, the photons **20** are funneled to and/or out the apex of the trumpet reflector **70** where they impinge on the photodetector means **22** positioned there.

With reference to FIGURE 6, the system for measuring radiation **10** is shown within a medical imaging environment (e.g., a CT scanner) used for examining subjects **50** (e.g., humans). In the usual manner, the subject **50** is positioned within a volume defined by a gantry **52**. A plurality of scintillators **16** and photodetector means **22** are positioned within the gantry **52** and configured to completely or partially surround the subject **50**. In this embodiment, the system **10** is contemplated to include a plurality of scintillators **16** and photodetector means **22**. Respective pairs of the scintillators **16** and photodetector means **22** are positioned between a plurality of plates **54** (e.g., tungsten plates). However, other configurations are also contemplated. Although it is not illustrated, it is to be understood that a radiation source (e.g., an x-ray tube) is also incorporated into the medical imaging environment in the usual manner.

It is also contemplated to also incorporate the system for measuring radiation of the present invention into other types of imaging scanners (e.g., PET and/or SPECT scanners, nuclear and/or gamma cameras, etc.) and exploratory oil well drilling detectors.

Faster scintillators convert x-rays to UV photons, which matches the UV responsivity of SiC photodiodes. However, it is to be understood that direct conversion without a scintillator is also contemplated.

The invention has been described with reference to the preferred embodiment. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

WHAT IS CLAIMED IS:

1. A radiation detector, comprising:
a scintillator which produces UV photons in response to receiving radiation from a radiation producing source; and
a wide bandgap semiconductor device sensitive to the UV photons produced by the scintillator, said semiconductor device producing an electric signal as a function of the amount of UV photons incident thereon.
2. The radiation detector as set forth in claim 1, wherein the wide bandgap semiconductor device is a SiC, GaN or AlGa_N device.
3. The radiation detector as set forth in claim 2, wherein the semiconductor device is a photodiode or an avalanche photodiode.
4. The radiation detector as set forth in claim 3, wherein the semiconductor device is an array of photodiodes or avalanche photodiodes.
5. The radiation detector as set forth in claim 1, wherein the wide bandgap semiconductor device has a dark current less than or equal to about 1.0 pA/cm² at about 0.5 VR.
6. The radiation detector as set forth in claim 1, wherein the wide bandgap semiconductor device includes a bandgap greater than or equal to about 2 eV.
7. The radiation detector as set forth in claim 1, wherein the wide bandgap semiconductor device includes a bandgap equal to about 3 eV.

8. The radiation detector as set forth in claim 1, wherein an output of the UV photons from the scintillator substantially matches a responsivity of the wide bandgap semiconductor device.

9. The radiation detector as set forth in claim 1, wherein the scintillator includes Li_2HfO_3 , BaF_2 , CsI , CeF_3 , $\text{LuAlO}_3:\text{Ce}^{3+}$, or $\text{Lu}_3\text{Al}_5\text{O}_{12}:\text{Pr}^{3+}$.

10. The radiation detector as set forth in claim 1, wherein the radiation includes at least one of gamma rays and x-rays.

11. A method of detecting radiation, comprising:
receiving radiation from a source;
producing UV photons in response to the received radiation;
directing the UV photons to a wide bandgap semiconductor device which is sensitive to the UV photons; and
generating an electric signal with the wide bandgap semiconductor device, said signal being a function of the amount of UV photons incident on the semiconductor device.

12. The method of detecting radiation as set forth in claim 11, further including:
limiting a dark current of the wide bandgap semiconductor device to be less than or equal to about 1.0 pA/cm^2 at about 0.5 VR.

13. The method of detecting radiation as set forth in claim 11, wherein a bandgap of the wide bandgap semiconductor device is greater than or equal to about 2 eV.

14. The method of detecting radiation as set forth in claim 11, wherein a bandgap of the wide bandgap semiconductor device is greater than or equal to about 3 eV.

15. The method of detecting radiation as set forth in claim 11, further including:

substantially matching an output of the UV photons to a responsivity of the wide bandgap semiconductor device.

16. The method of detecting radiation as set forth in claim 11, wherein the wide bandgap semiconductor device includes SiC, GaN or AlGaN.

17. The method of detecting radiation as set forth in claim 11, wherein the UV photons are produced by a scintillator that has the received radiation incident thereon, said scintillator including Li_2HfO_3 , BaF_2 , CsI, CeF_3 , $\text{LuAlO}_3\text{:Ce}^{3+}$, or $\text{Lu}_3\text{Al}_5\text{O}_{12}\text{:Pr}^{3+}$.

18. A system for measuring radiation, comprising:
means for producing a number of UV photons in response to received radiation, said number of UV photons being proportional to a level of the radiation; and
means for producing an electric signal as a function of the number of the UV photons.

19. The system for measuring radiation as set forth in claim 18, wherein the received radiation is gamma rays or x-rays.

20. The system for measuring radiation as set forth in claim 18, wherein the means for producing the electric signal includes a wide bandgap semiconductor device sensitive to UV photons.

21. The system for measuring radiation as set forth in claim 18, wherein the means for producing the number of UV photons includes a scintillator, said scintillator including Li_2HfO_3 , BaF_2 , CsI , CeF_3 , $\text{LuAlO}_3\text{:Ce}^{3+}$, or $\text{Lu}_3\text{Al}_5\text{O}_{12}\text{:Pr}^{3+}$.

22. The system for measuring radiation as set forth in claim 21, the system further including:

a reflector, said reflector focusing the UV photons from the scintillator onto the means for producing the electric signal.

23. The system for measuring radiation as set forth in claim 18, wherein the system is incorporated into one of a medical imaging apparatus or an oil exploration drilling apparatus.



SIC PHOTODIODE DETECTORS FOR RADIATION DETECTION APPLICATIONS

ABSTRACT OF THE DISCLOSURE

A radiation detector includes: a scintillator which produces UV photons in response to receiving radiation from a radiation producing source; and, a wide bandgap semiconductor device sensitive to the UV photons produced by the scintillator. The semiconductor device produces an electric signal as a function of the amount of UV photons incident thereon. Preferably, the electric signal is then measure, recorded and/or otherwise analyzed.

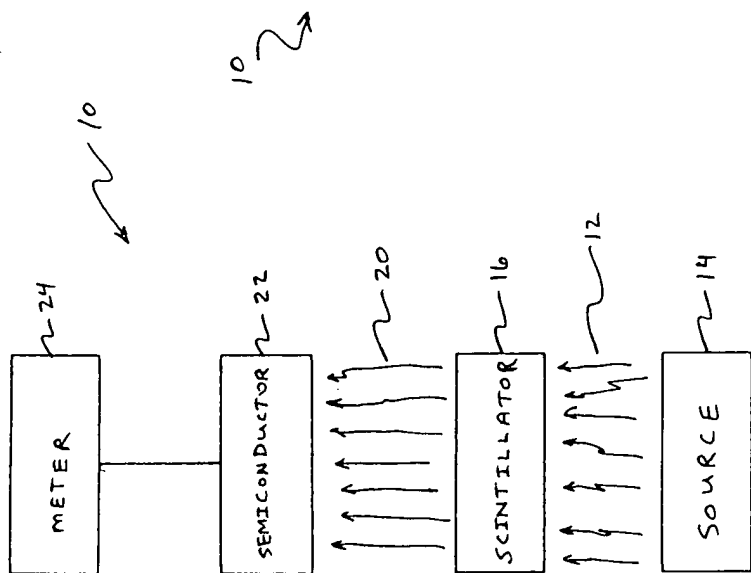


FIG. 1A

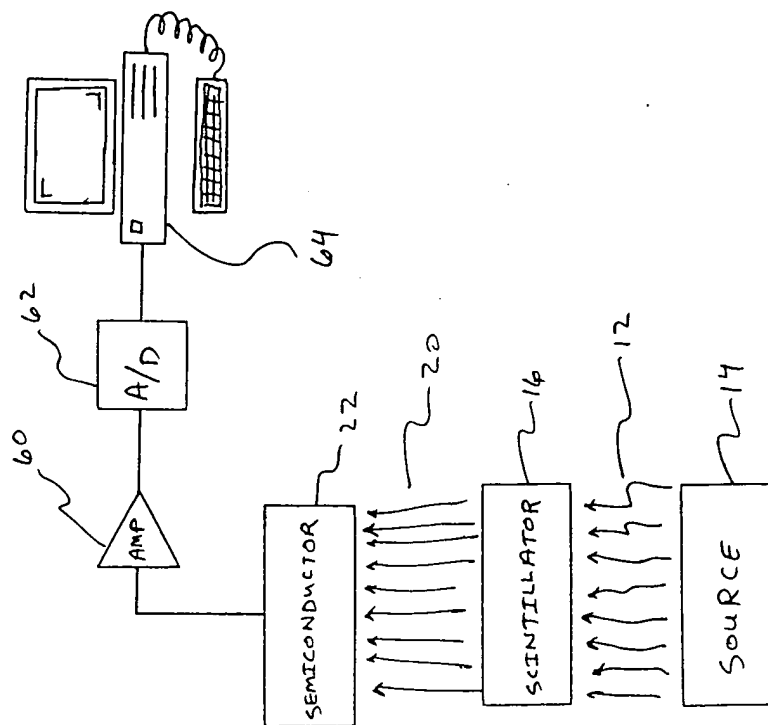


FIG. 1B

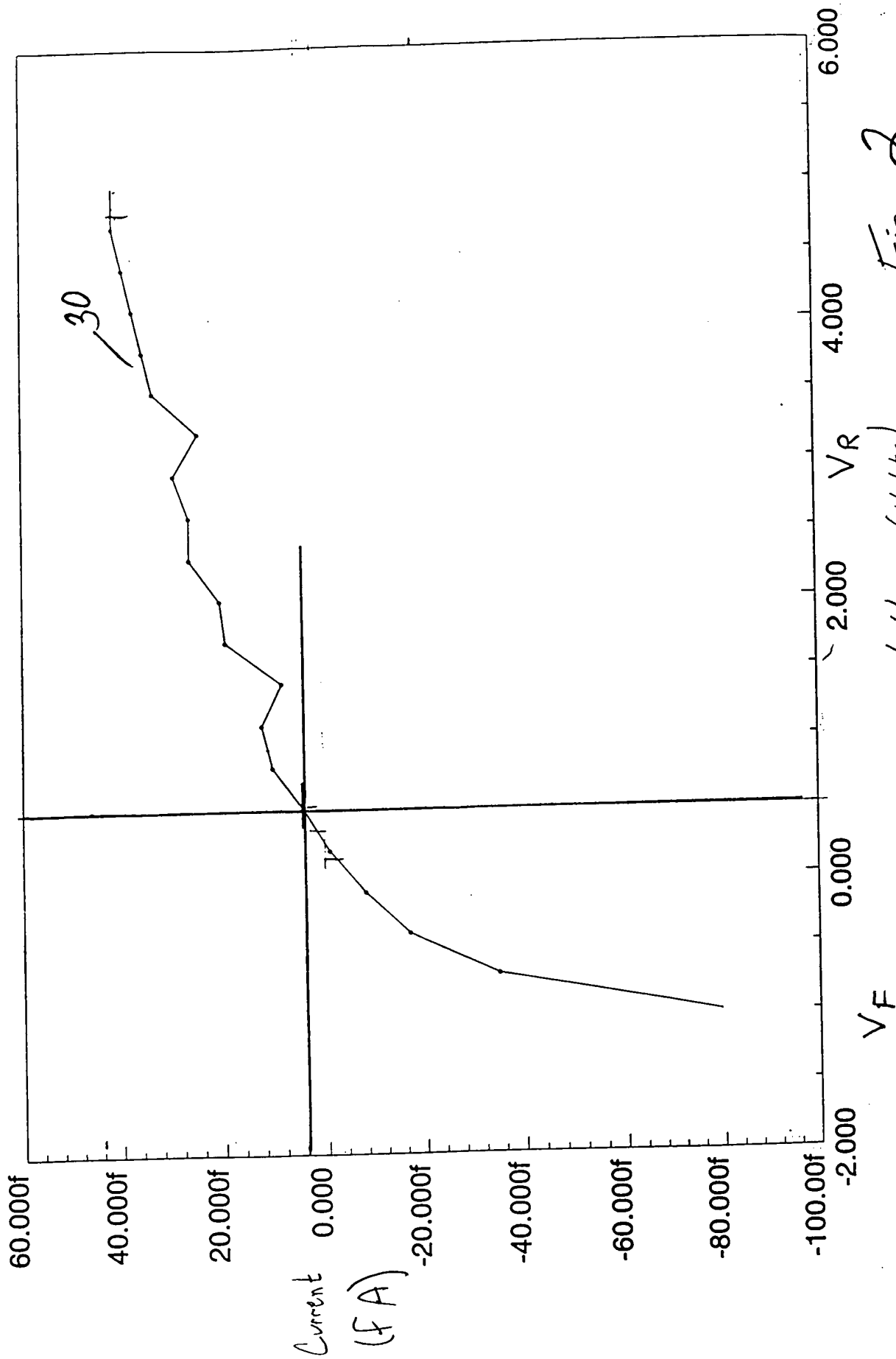


Fig. 2

Voltage (volts)

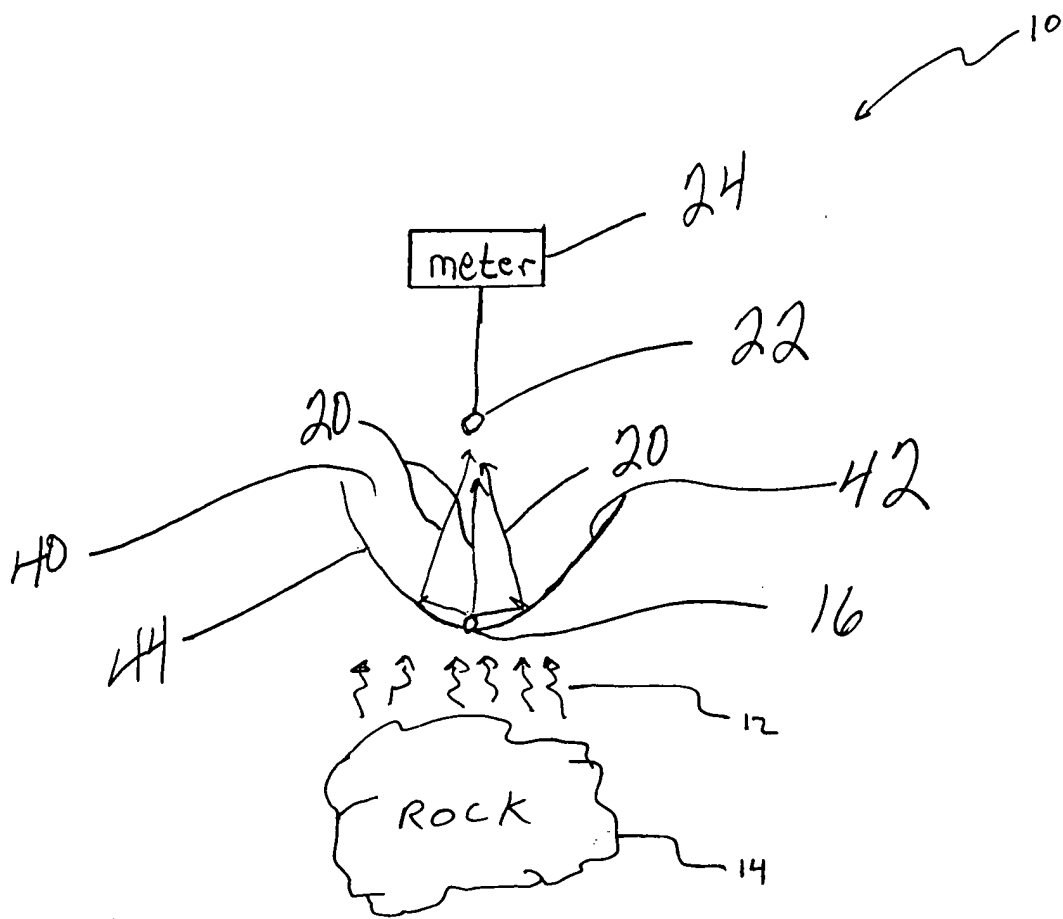


Fig. 3

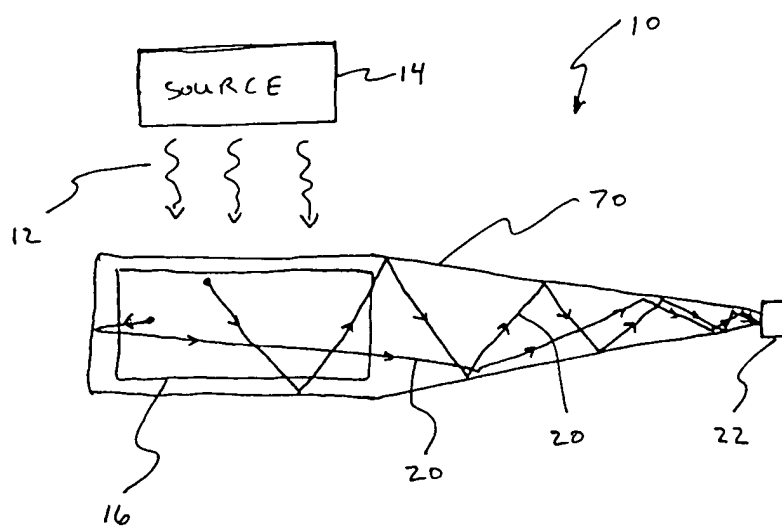


FIG. 5

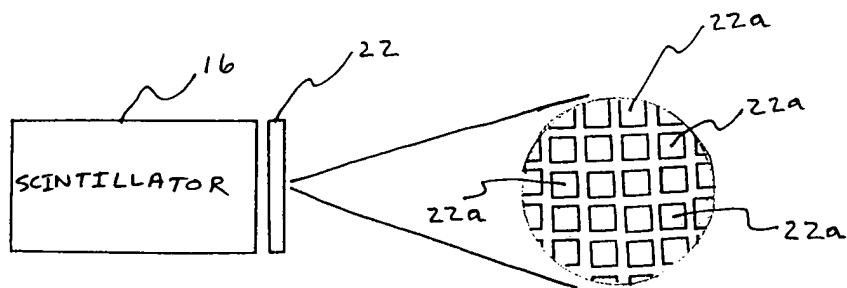


FIG. 4

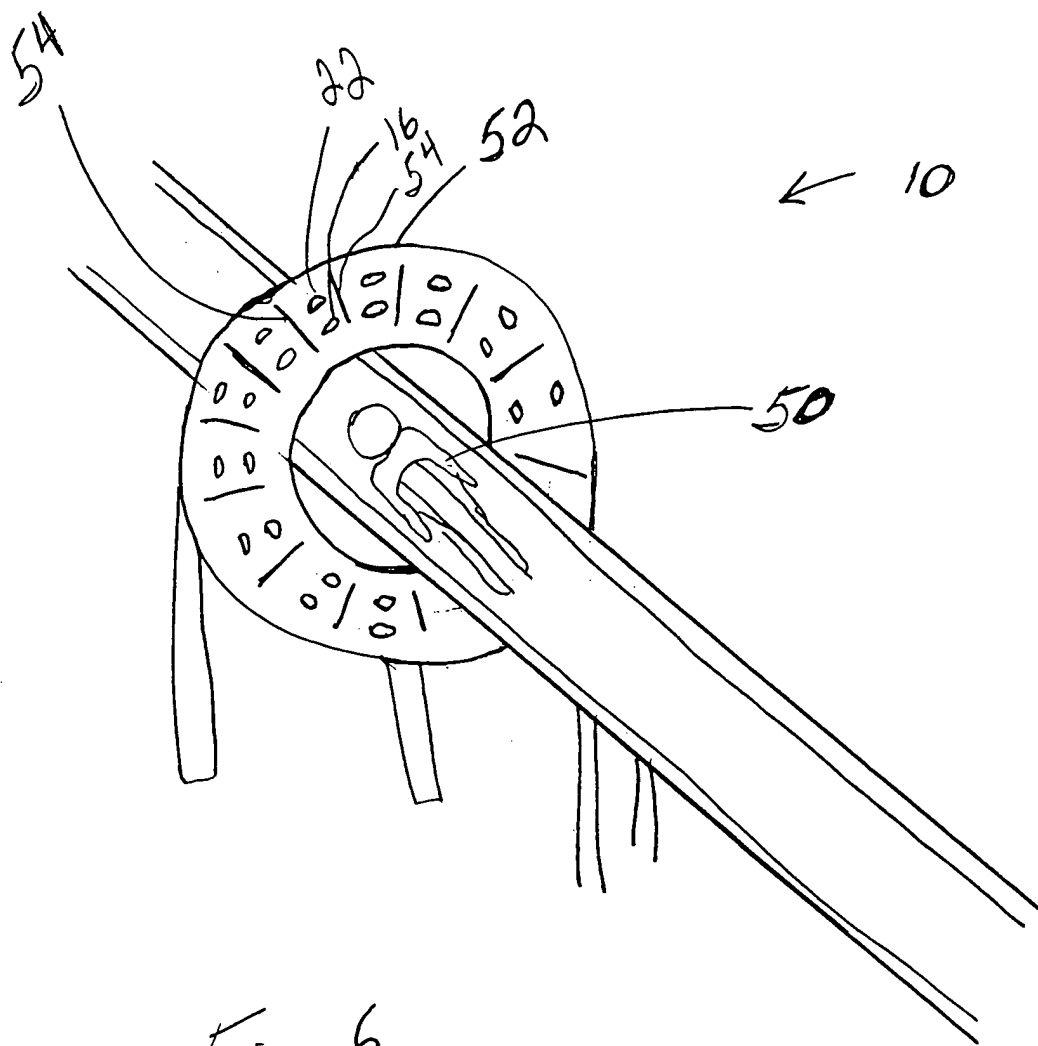


Fig. 6